

Single-Strand Excitation for Probing Current Sharing and Parallel Resistance in Cored Nb₃Sn Rutherford Cables at 4.2 K and 10 Tesla

C. Kovacs, M. D. Sumption, E. W. Collings

Abstract— A rig was fabricated to test single-strand excitation and current sharing in Nb₃Sn Rutherford Cables. Measurements were performed on 400 mm lengths of a 27-strand, cored cable. In preparation for measurement, the cable was mounted onto a U-shaped holder, reacted for 72-48-50 h at 210-400-665 °C under 20 MPa. Current was injected into a single strand of the cable, and the onset of current sharing was seen above single strand I_c . After the onset of transition the I - V showed a flat baseline the slope of which gave the transfer resistance to the two neighboring strands. Two cable samples were measured, one of which was reacted in a dilute oxygen atmosphere. The slightly oxidized cable had a $R_{//}$ of 280 nΩ whereas the other sample had a $R_{//}$ was 70 nΩ per lay pitch. Varying I/I_c and a heat pulse from a carbon paste heater was used to turn off successive pairs of neighboring strands, and the resulting current-distribution was measured using voltage taps. These measurements were performed as a screening for cable and cable preparation protocol for larger scale measurements.

Index Terms— Critical Current Measurement, LTS Cables, Niobium compounds, Nb₃Sn Wire, Stability.

I. INTRODUCTION

THE STABILITY of cables depends on the ability of strands to share current across their interstrand contact resistances (ICR). In a Rutherford cable ICR is a function of the strand-cross-over resistance R_c and the side-by-side resistance R_a . The former is made sufficiently large to control M_{coup} and its contribution to a dynamic b_3 field harmonic during magnet ramping. Making both R_c and R_a sufficiently small ensures adequate current sharing and stability for safe operation. Focusing primarily on field error, our group has made numerous AC-loss-based ICR measurements of Nb₃Sn cables in response to: preparation condition [1]-[3], the presence of various types of core [4]-[10], variation of core width [8][11]-[13] and placement [11][13]. But not directly considered were the influences of these variables on current sharing and stability [14]. The latter is quantified in terms of a “minimum quench energy density” (MQE), the locally deposited energy just sufficient to create a local quench. Heat pulses of increasing energy are applied to one cable strand

carrying a fixed reduced current $i = I/I_c$ until quench takes place. The test is repeated at increasing values of i . While several such measurements have been made on Nb-Ti [15][16] and Nb₃Sn cables [17] the impacts on its stability from: (i) *cable preparation conditions*, (ii) *core types, width, and placement* have not been explored. MQE testing in facilities like CERN’s FRESCA2 [17]-[19] are complicated and expensive. To enable less expensive measurements, our group has developed a compact probe for insertion into the bore of a 15 T solenoid. In this paper initial measurements are shown with two different preparation conditions.

In a future version of the experiment, we plan to use a superconducting transformer to excite the cable as a whole. However, in this first version, both ends of a *single strand* of the cable are brought out and secured to current leads. A spot heater is attached to this strand and voltage taps or (in the future) Hall sensors are applied to the others. The heater power is increased until a local quench is achieved and current is shared with neighboring strands. As i is increased more (above unity), and more strands become engaged in the sharing, eventually the neighboring strands become overloaded to the point of full quench. Current transferring across the cable was detected by voltage taps. Since only one strand was excited the full cable MQE was not measured, nevertheless these experiments enable *current sharing* for various cable types and for preparation conditions to be assessed.

We plan to replicate the cable preparation conditions to be used in future AC-loss-based ICR measurements. Analysis of the results of the measurements will provide a useful description of the dependence of current sharing on ICR.

II. EXPERIMENTAL

A. Cable Samples and Preparation for Measurement

A 800 mm length of F095 Rutherford cable was cut from a spool. The cable had 27 strands, was 14.2 x 1.78 mm, and had a stainless steel (SS) core, further specifications are given in Table 1. The cable was preformed into the U-shape for the probe with a preforming press and a pressure of less than 10 MPa was applied. Care was taken to prevent cable splaying from both 5 mm radius bends in the U-shape preforming press. The cable was wrapped in a triple layer of S-glass tape. The bottom of the 316 SS sample holder was pressed to 20 MPa and Ti fasteners were tightened to hold the pressure. After

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this, the sides of the sample holder were pressed to 20 MPa and Ti fasteners we used to hold the pressure. An additional set of outer 316 SS plates were tightened with a small amount additional pressure to prevent possible high temperature creep in the Ti fasteners. A picture of the sample holder is shown in Fig. 1 and a CAD drawing is shown in Fig. 2.

On both ends of the cable, all the strands but one were removed over a distance of 200 mm. The uncut strand was then wrapped around a copper current lead, held in place with 316 SS wire (and after heat-treatment soldered down). This strand was later used for current excitation. Details of the sample heat-treatment are shown in Table 1.

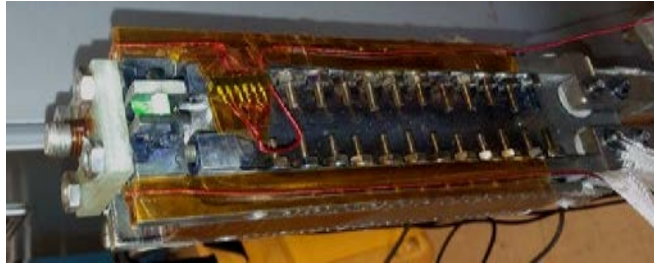


Fig. 1. Single strand excitation cable probe with sample attached and fully instrumented.

After heat-treatment, the outer 316 SS pressing plates were removed. Additionally, Ti slides were removed to allow access for instrumentation: carbon-paste heaters, voltage taps, and Type-E thermocouples.

Two separate samples were prepared for and then measured on the probe, measurement #1 (M1) and measurement #2 (M2).

TABLE I
DETAILS OF CABLE SAMPLE AND SAMPLE PREPARATION

Strand	
Type	OST-RRP Billet# 8853-2616
Dia, mm	1.0
Filament count	60/61
Filament Dia, μm	110
Cable	
Strand count, #	27
Keystone angle, deg	0.95
Compaction, %	87
Width, mm	14.2
Thickness ave, mm	1.78
Transposition pitch, mm	110.2
Core material	316 S.S.
Core width, mm	10.8
Core thickness, μm	25
Sample Prep	
Pressure, MPa	20
Heat treatment	210-400-665 °C for 72-48-50 hrs. Under Ar atmosphere in S.S. retort
Epoxy impregnation	No epoxy

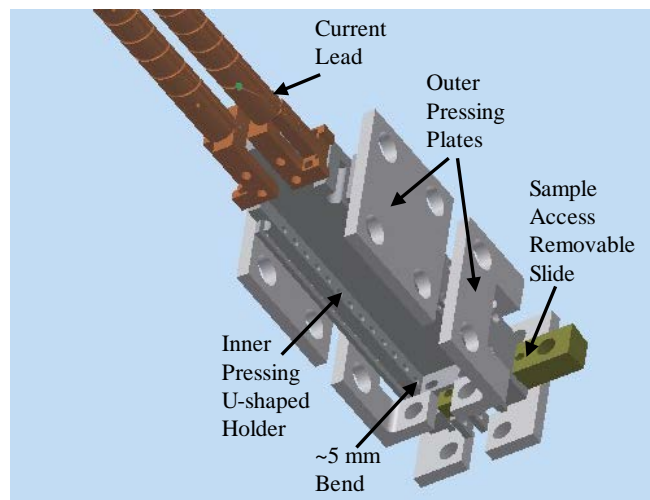


Fig. 2. Single strand excitation cable probe CAD assembly.

The cable itself was from the same spool, but M1 was prepared with a slight oxidation on the surface of the strands due to a poorly sealed retort while M2 had a cleaner Ar atmosphere in the retort.

B. Instrumentation and Measurement of Cable ICR

M1 and M2 had different instrumentation diagrams, both shown in Fig. 3. M1 had a dual set of seven transverse voltage taps with a transverse gauge of ~ 1 mm and a longitudinal gauge of 25 mm. Additionally, there were voltage taps at each end of the excited strand right before it entered the cable, a 400 mm gauge. M2 had a carbon paste heater on the excited strand and voltage taps at each end of the excited strand right before it entered the cable. Voltages were monitored using Keithley 2182A nanovoltmeters. The probe was precooled in LN2 and then placed in a 4.2 K LHe bath within an Oxford research 60 mm bore solenoid magnet. All measurements were performed at 10 T.

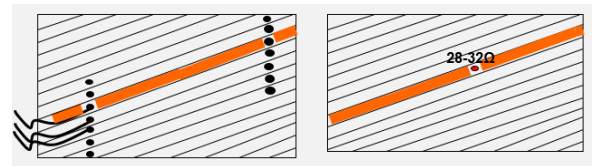


Fig. 3. Instrumentation schematic of M1 (left) and M2 (right). For both measurements, there was also voltage taps at the far ends (gauge ~ 400 mm) of the cable.

III. RESULTS

A. Measurement 1: ICR

The I-V results of M1 are shown in Fig. 4 and Fig. 5. The single strand I_c was 500 A, after which current sharing began with the first nearest neighbors. The slope of the region above 500 A, determined using a linear fit, was taken as half of the resistance to the nearest neighbors.

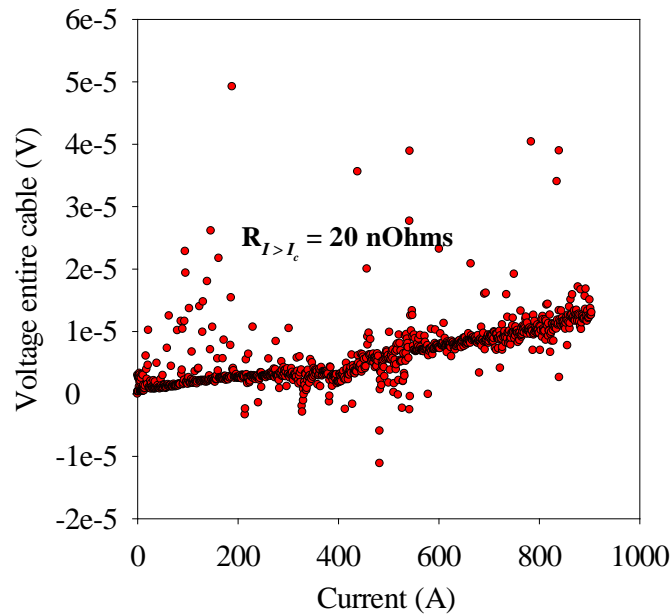


Fig. 4 M1 measurement of I - V for single strand excitation, voltage end-to-end, 400 mm gauge length. Seen is initial portion below excited strand I_c (500 A) as well as portion above initiation of current sharing (orange dashed line), where the interstrand contact to the nearest neighbor strands can be extracted from the slope.

Fig. 5 shows data from the transverse voltage tap pairs and demonstrates that most of the current was transferred to the first nearest neighbors during I - V measurements without heater pulses. This information was used during M2 to determine the width of the normal zone during heat-pulse measurements. The noise of M1 in Fig. 4 is substantially larger than that of M2 in Fig. 6, even though they were measured in an identical fashion. This might be due to the oxidation of M1 and increased instability of individual strands.

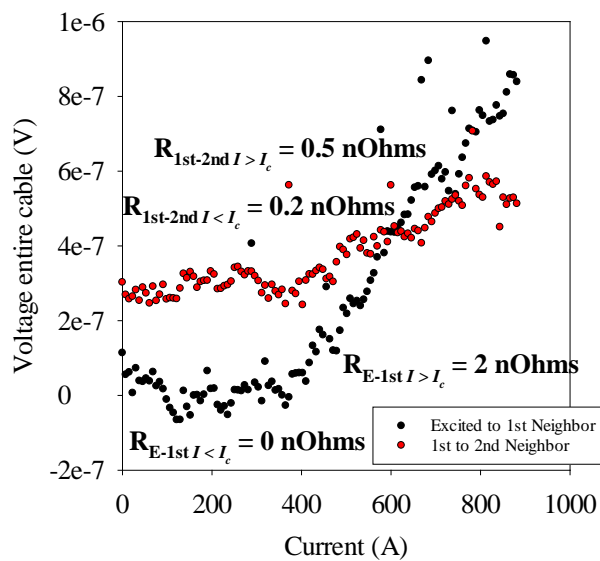


Fig. 5. M1 transverse voltages during single strand excitation. The figure shows that the majority of the current flows to the neighboring strands, but that a small fraction goes to the next nearest neighbors as well.

The cable had a SS core, and thus R_c was quite high, and the data was interpreted in terms of current sharing to neighboring strands on the cable surface. This sample had 7 lay pitches, making the side-by-side resistance, $R_{//}$, per lay pitch 14 x the R extracted from the slope of Fig. 4, giving an $R_{//}$ of 280 n Ω .

B. Measurement 2: $R_{//}$ and Width of Current Transfer

Fig. 6 shows I_c data from M2. The single-strand I_c was 600 A at 4.2 K and 10 T. The slope afterwards was 5 n Ω , giving a $R_{//}$ of 70 n Ω . Variable i was applied and heat pulses of different times and energy were used to create different amounts of current sharing. Fig. 7 and 8 show this data. Assuming all of the neighboring strands had the same $R_{//}$, the number of nearest neighbors the current sharing traversed could be determined. current sharing traversed could be determined.

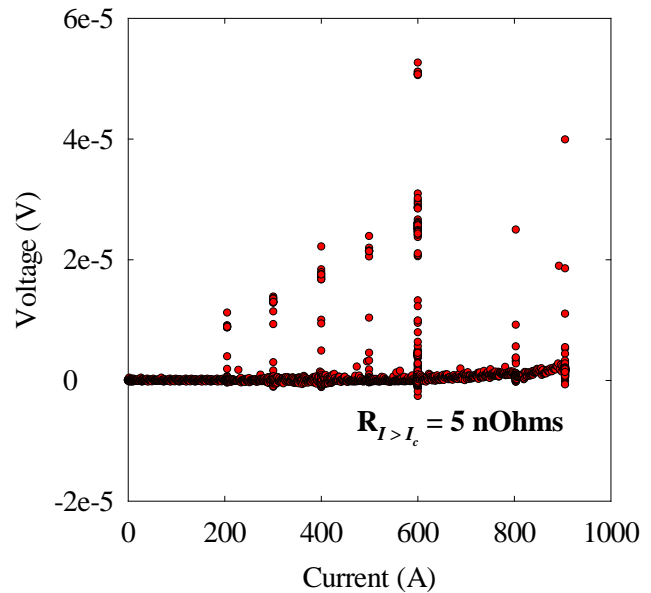


Fig. 6. M2 I - V curve. Single strand I_c at 600 A. Slope above I_c can be used to extract current sharing and ICR to neighboring strands. Large peaks are from heater pulses.

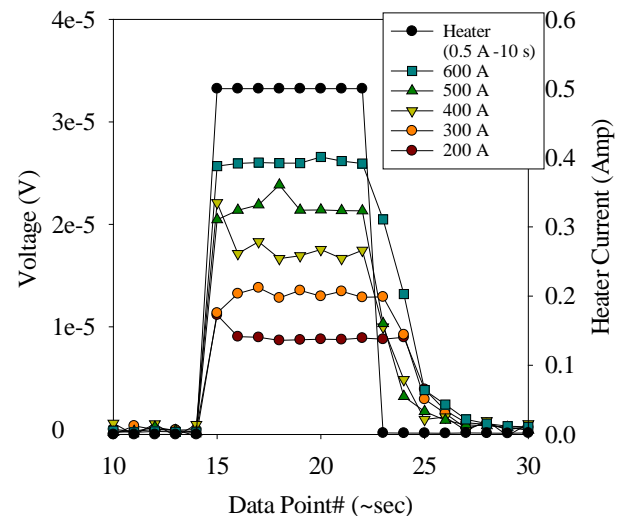


Fig. 7. Normal Zone formation with Heater 0.5 A (30 J deposition).

Very large voltages were generated at high i and heater pulse energy; this was associated with the normal zone traversing the entire cable cross-section. The sample didn't quench under these conditions due to the amount of stabilizing copper throughout the Rutherford cable cross section.

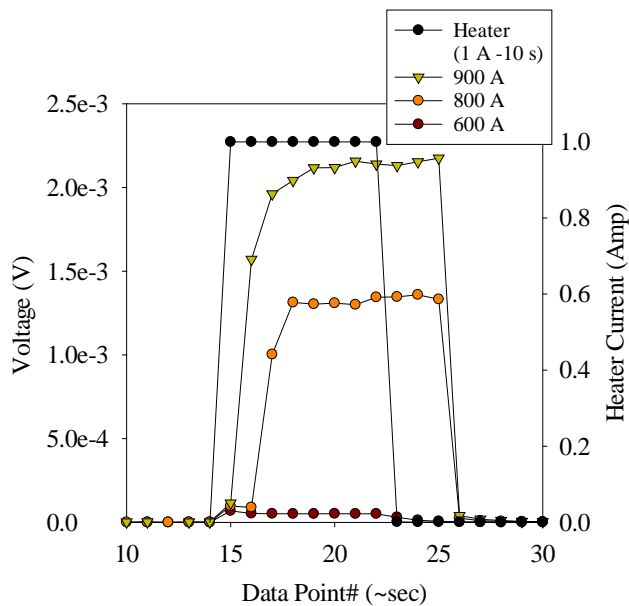


Fig. 8. Normal zone formation with Heater 1 A (120 J deposition).

IV. DISCUSSION OF THE RESULTS

$R_{//}$ for M1 was approximately four times larger than $R_{//}$ for M2. The increase in partial pressure of oxygen and increased oxidation on the M1 strand surfaces contributed to this increase. The recommended $R_{//}$ of greater than 200 n Ω per lay pitch was only met by the partially oxidized M1 [20]. Table II shows the predicted width of the current sharing for varying i and heat pulse energy deposition. The number of strands shared to (double that of the nearest neighbor shared to) is determined by dividing the resistance in the cable during the heat pulse by the resistance seen in Fig. 6. The sudden increase in voltage from $i = 1.26$ to $i = 1.68$ with 120 J of deposited energy was due to the normal zone totally traversing the cable.

TABLE II
PREDICTED WIDTH OF CURRENT SHARING GENERATED DURING M2 HEAT PULSES AT VARYING I/I_c

i	Heater (J)	Voltage (V)	Nearest neighbor shared to (#)
0.42	30	8.78E-06	5
0.64	30	1.31E-05	5
0.84	30	1.70E-05	5
1.06	30	2.15E-05	5
1.26	30	2.60E-05	5
1.26	120	5.10E-05	11
1.68	120	1.33E-03	Entire Cable
1.90	120	2.10E-03	Entire cable

$I_c^{\text{est}} = 600 \text{ A}$

The heater energies in this experiment were orders of magnitude larger than heater energies used during MQE measurements for fully excited Nb₃Sn cables [21]. This is because only a single strand was excited, i.e. i of the entire cable was less than 0.05. At this low of a current density, and in direct LHe contact over such a large length and strand area, the amount of high RRR copper within the Rutherford cable appears to be enough to make the sample cryostable.

V. SUMMARY

We have designed a fixture and performed single-strand excitation measurements on Nb₃Sn Rutherford Cable under magnet relevant conditions. For a slightly oxidized cable, the resistance with the nearest neighbor per lay pitch was 280 n Ω . For a less oxidized sample the resistance with the nearest neighbor was 70 n Ω per lay pitch. Transverse current sharing occurred due to normal zones formation, and the width of the current sharing was determined for varying i and heat pulse energy deposition.

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